
Reactions on Excited States using the National Ignition Facility

L.A. Bernstein
LLNL



Nuclear Astrophysics using NIF
August 28, 2007
LLNL

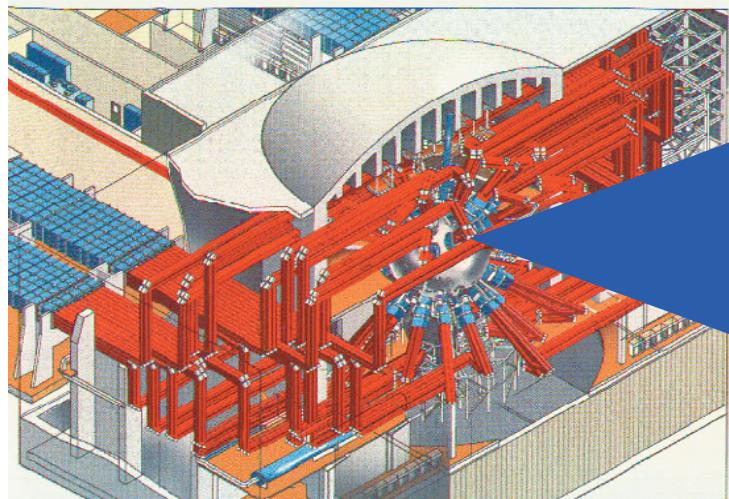
This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.



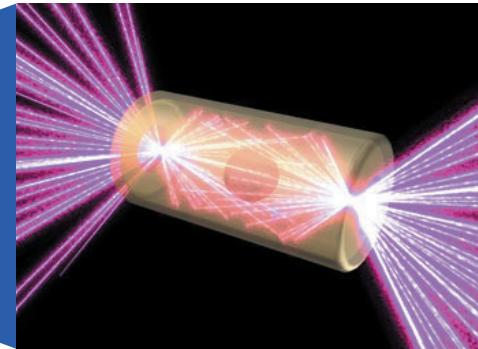
The National Ignition Facility (NIF): A new kind of nuclear physics laboratory

NIF is designed to implode D-T (or other) pellets to achieve thermonuclear fusion

Standard ignition configuration: 192 beams, 1.8MJ in 3ω light



Indirect drive: X-rays drive implosion

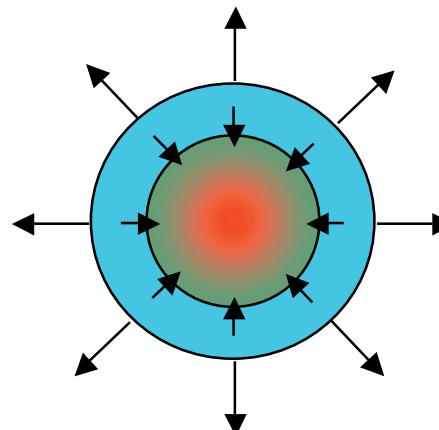
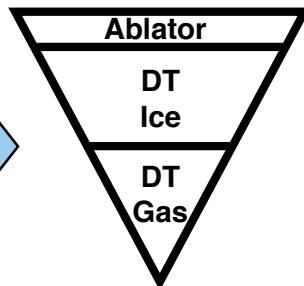
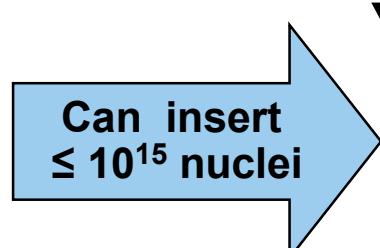


Hohlraum ~ 10 mm long

Target ~ 1 mm radius

Optical pulse \sim few ns

Burn \sim few ps



$$r_{initial} = 1 \text{ mm}$$
$$r_{final} = 30 \mu\text{m}$$

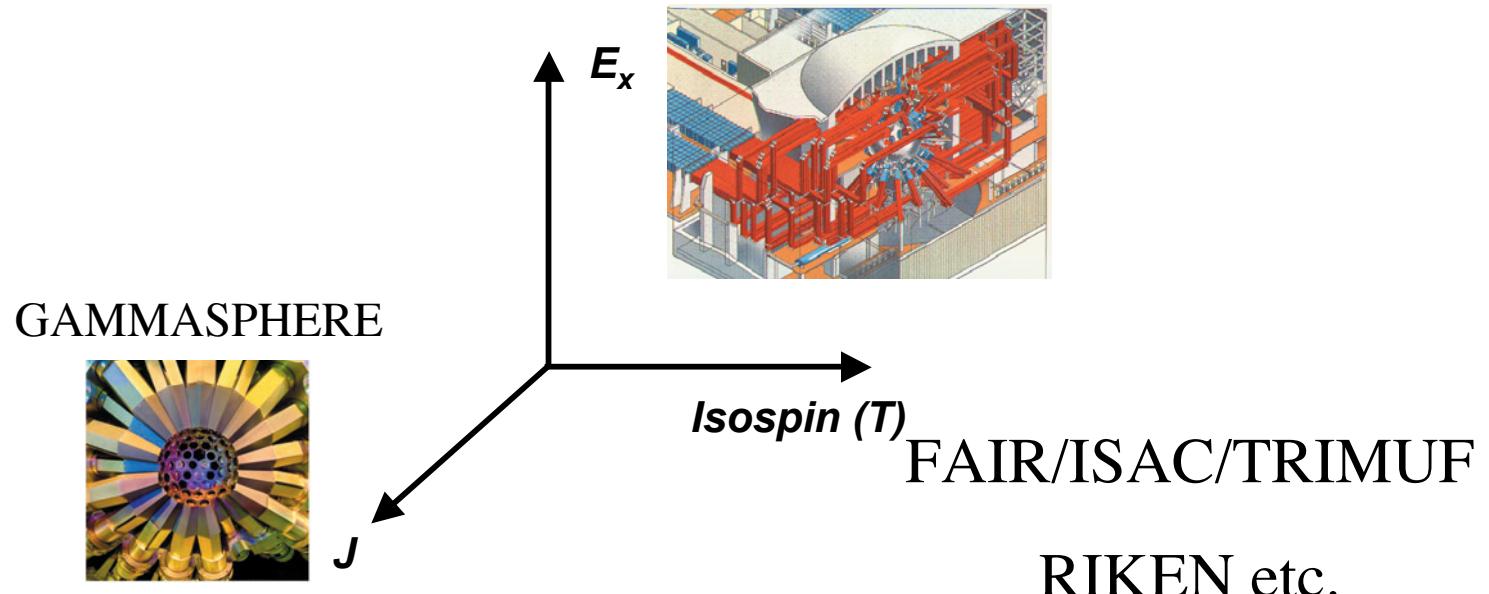
Up to 300 shots/year with $\approx 15\%$ dedicated for basic science (Ride-along also possible)

Outline



- How to study reactions on excited nuclear states using NIF
 - Radiochemical approach (toy model)
 - Neutron-induced reactions
 - Photon- (and electron-) induced reactions
- Physics topics that can be addressed
 - Spin-effects on s-process branch point (n,γ) cross sections
 - Properties of weakly bound nuclear states
 - Stimulated emission from nuclear isomers
 - Quasi-continuum nuclear properties (lifetimes, strength functions)

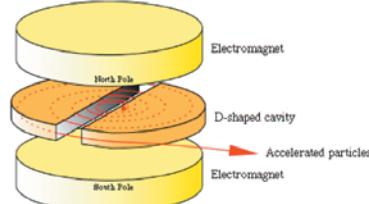
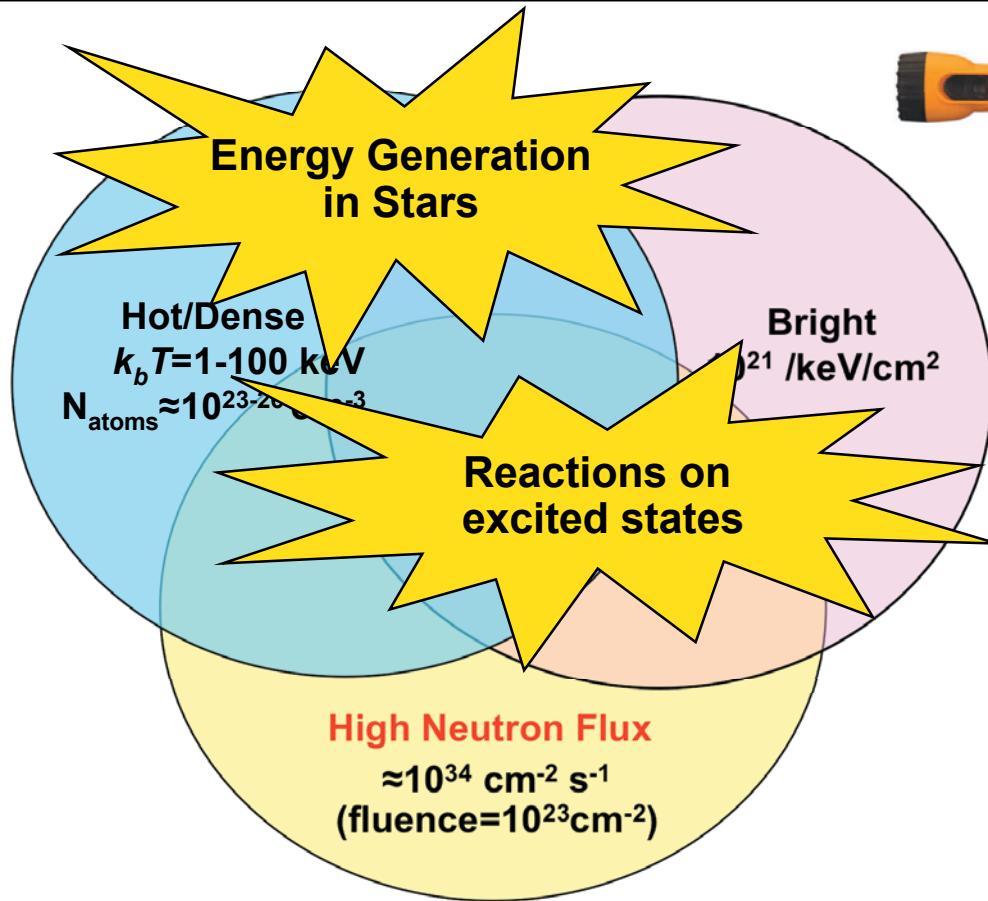
Scattering from excited states adds a new trick to our experimental “tool kit”



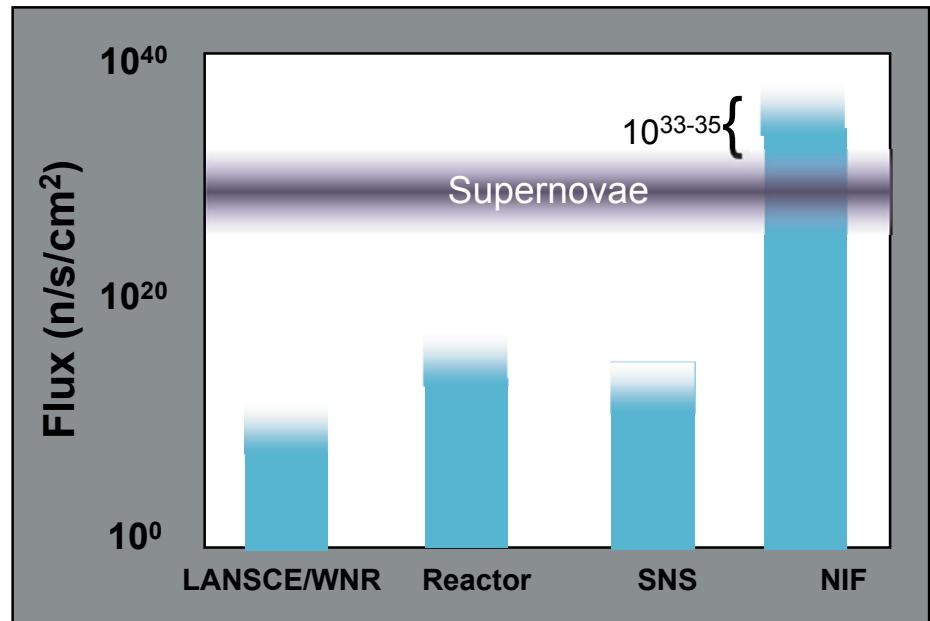
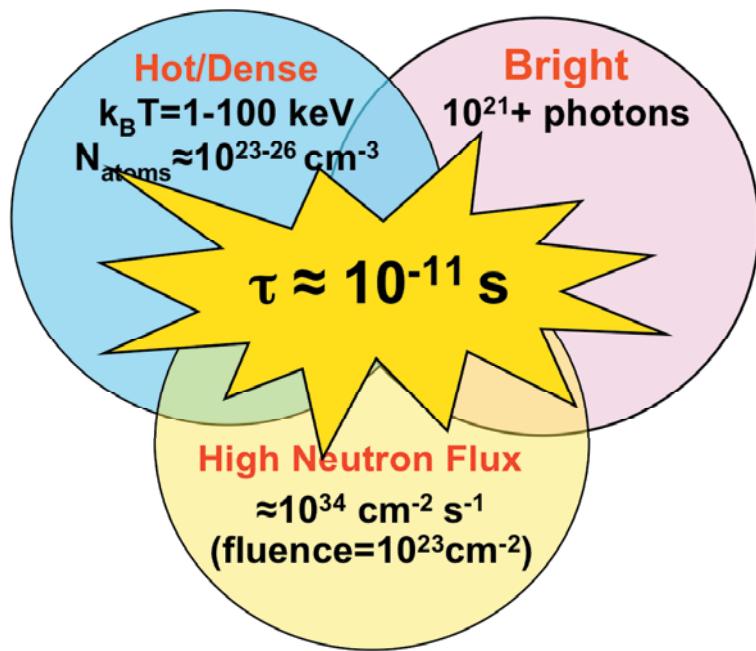
- Nuclear spin and parity have been explored actively
 - Spectroscopy using direct and heavy-ion reactions for J
 - RIBs (FAIR etc.) which probes N/Z far off stability for T
- E_x has only been explored passively (decay of excited states)

This is opens a whole new range of nuclear physics

NIF presents many new environments for nuclear physics and astrophysics

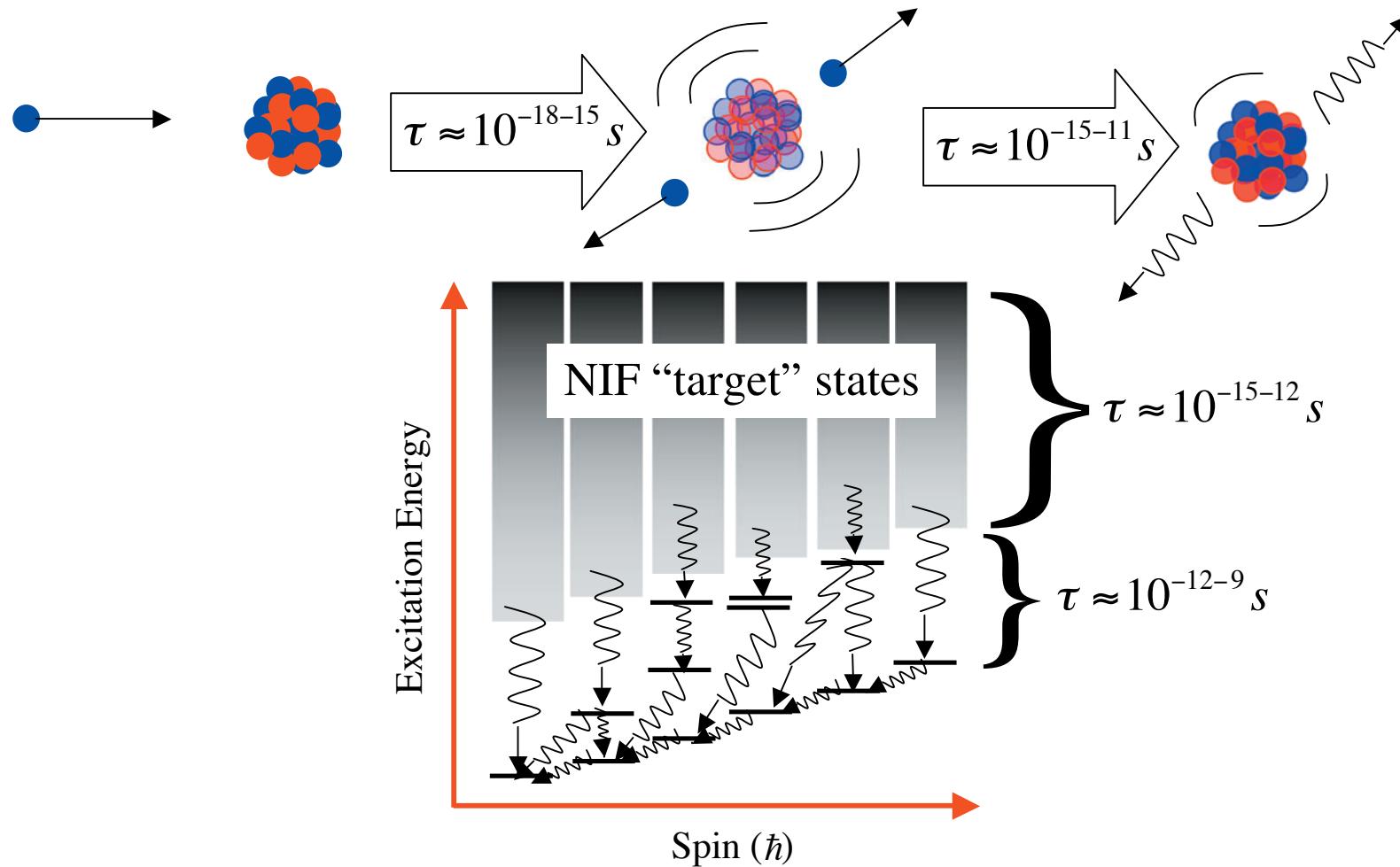


NIF compression (≈ 33) over a short burn time (10^{-12} s) opens other possibilities



This huge flux offers the possibility of studying reactions on very short-lived states

The short time scale of a NIF burn (τ_{burn}) matches the lifetime of “quasi-continuum” states (τ_{crit})



NIF will cause reactions on *non-isomeric* short-lived states

So what! Can you *measure* anything in this “Hand grenade in a trash can”?

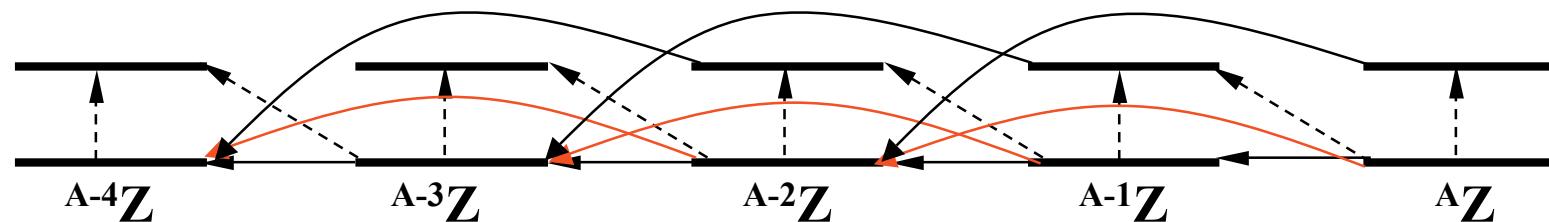


- “Prompt” observation of transitions following (n,xn) reactions at NIF is daunting (to say the least)
 - A commercial Silicon detector receives one Joule in 20 ps after a “nominal” shot!
 - Let’s not even talk about the EMP...
- Short term spectrum is swamped by chamber backgrounds:
 - $^{16}\text{O}(\text{n},\text{p})^{16}\text{N}$ produces 6 MeV γ -ray from decay of ^{16}N ($\tau \approx 7\text{s}$) etc.
- Best approach: Radiochemistry
 - “Seed” a nucleus whose multi-order (n,xn) products have long τ ($\gg 7\text{s}$)
 - Measure ratios of reaction products with the same Z (same $\epsilon_{\text{collection}}$)
 - Gases are best for collection purposes (see Stoyer talk)
 - Start by “piggy-backing” on Xe, Kr etc.

A simple model shows that reactions on excited states are responsible for most higher-order reaction products at NIF

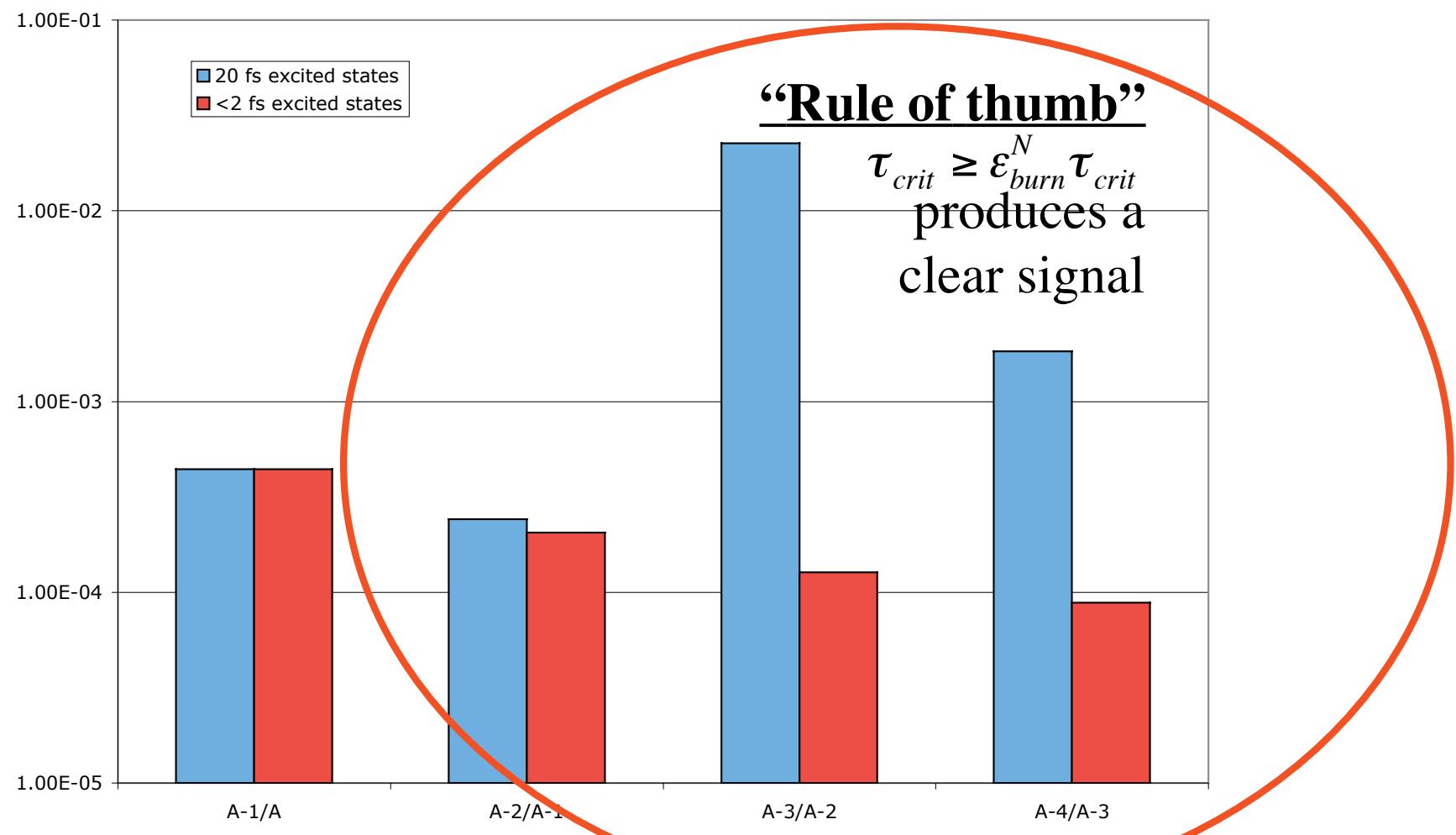


- Load a small number ($\leq 10^{15}$ atoms) of tracer nuclides into the capsule.
- Divide NIF “burn” time into 100 equal-flux time bins ($\Delta t \approx 50\text{-}400$ fs).
- Assume 14 MeV neutrons induce $(n,3n)$ rather than $(n,2n)$ on all nuclei still at $E_x \approx S_n$ after 1 bin and that these nuclei
- Include two neutron energy bins:
 - 14 MeV: can do (n,n') & $(n,2n)$ on ground and $(n,3n)$ on excited states
 - Tertiary ($E_n > 14$ MeV) neutrons (10^5 less than 14 MeV) do $(n,3n)$ on ground states



This type of analysis is quantitatively understood at LLNL

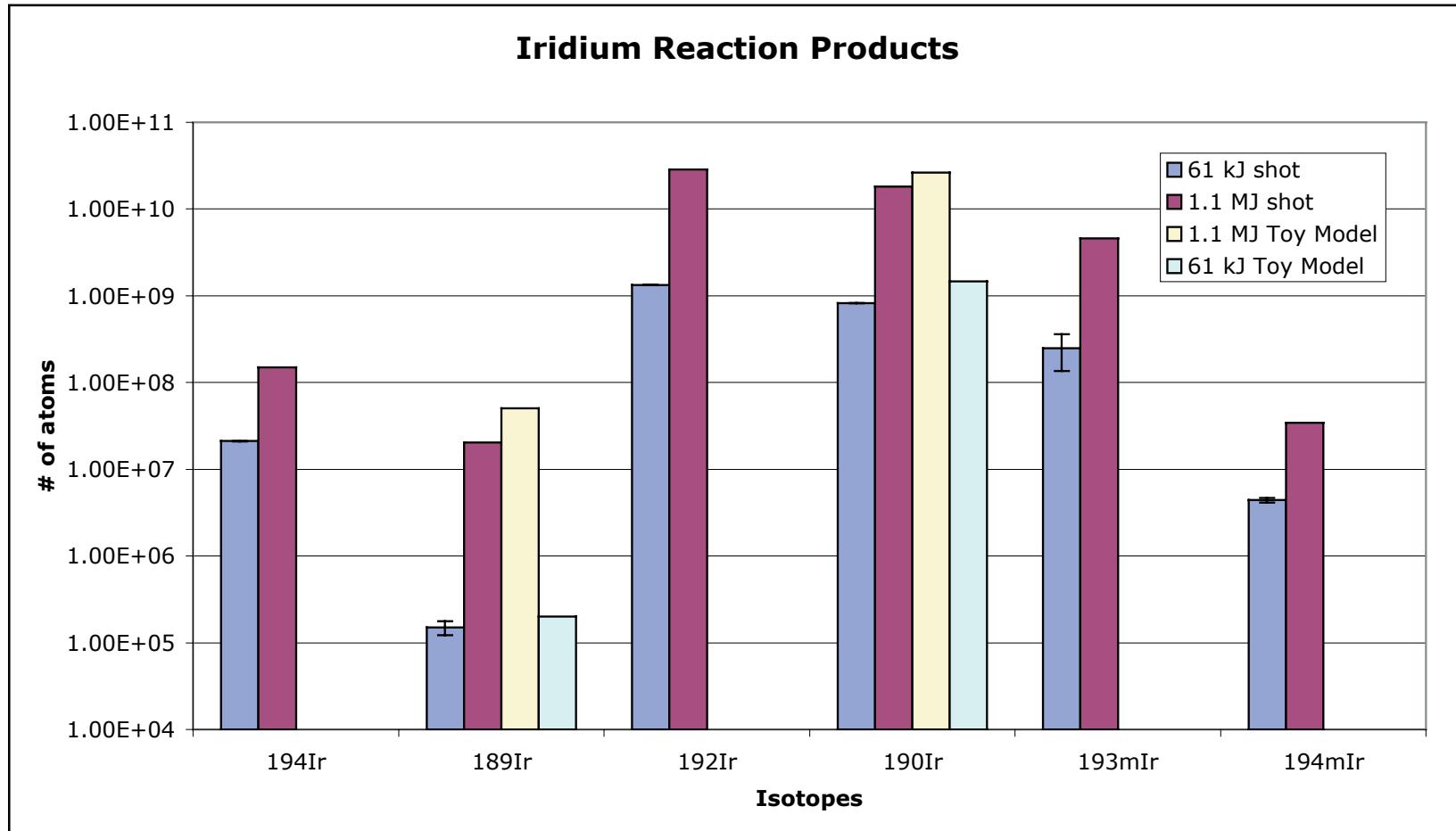
Almost all higher-order reaction products are from reactions on excited states with $\tau \geq 20$ fs



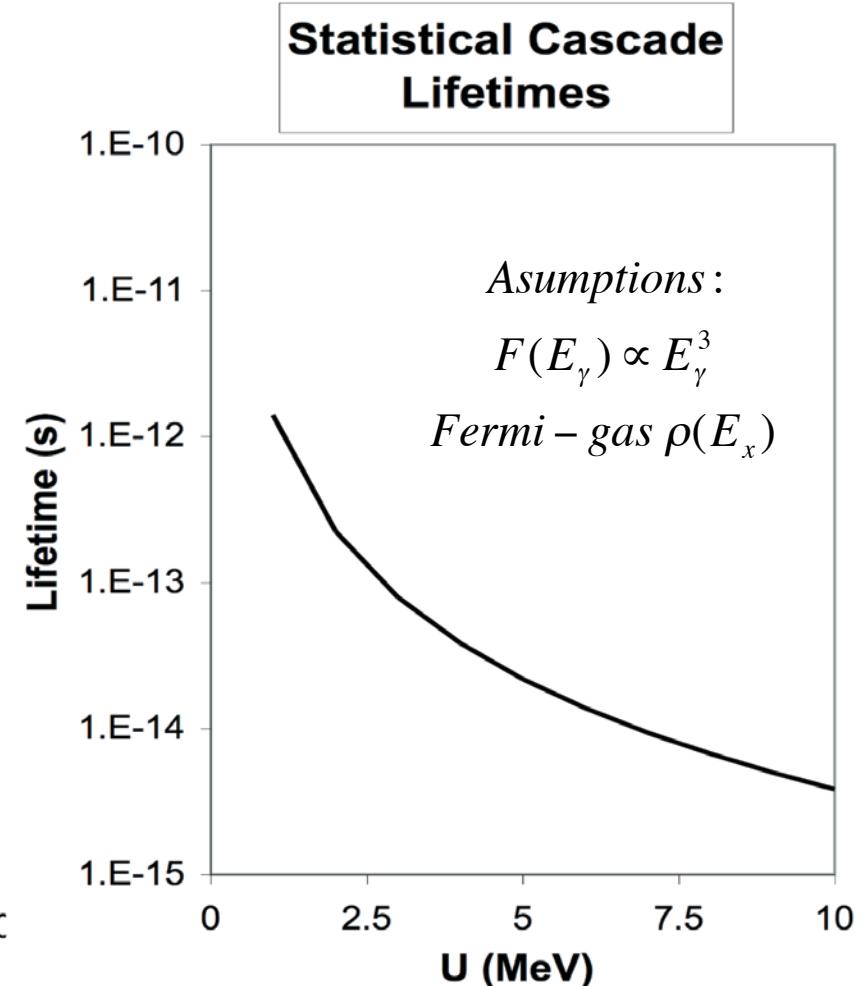
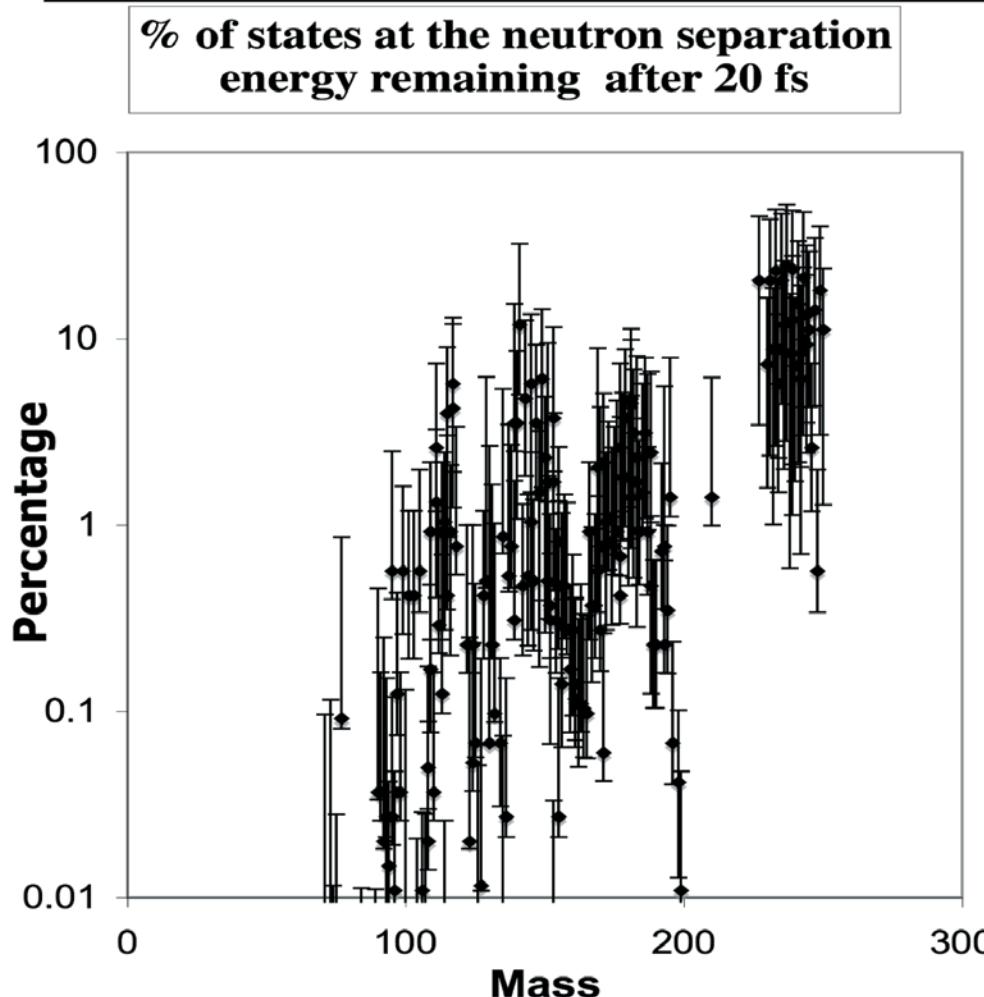


The toy model is surprisingly successful at reproducing the results of more sophisticated simulations

- 3×10^{13} atoms of Iridium doped into the ice-ablator interface.

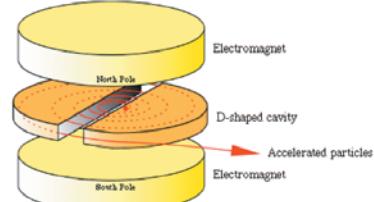
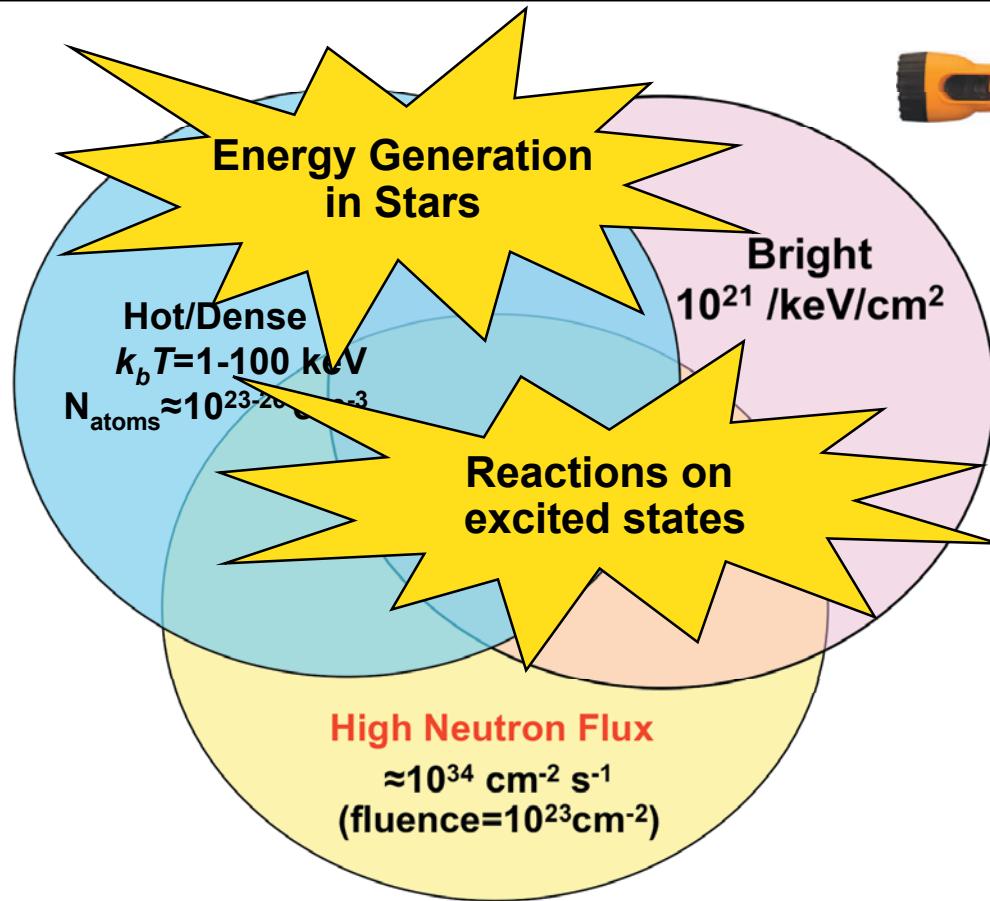


How does this τ_{crit} compare to lifetimes for states with $E_x \leq$ the neutron separation energy?

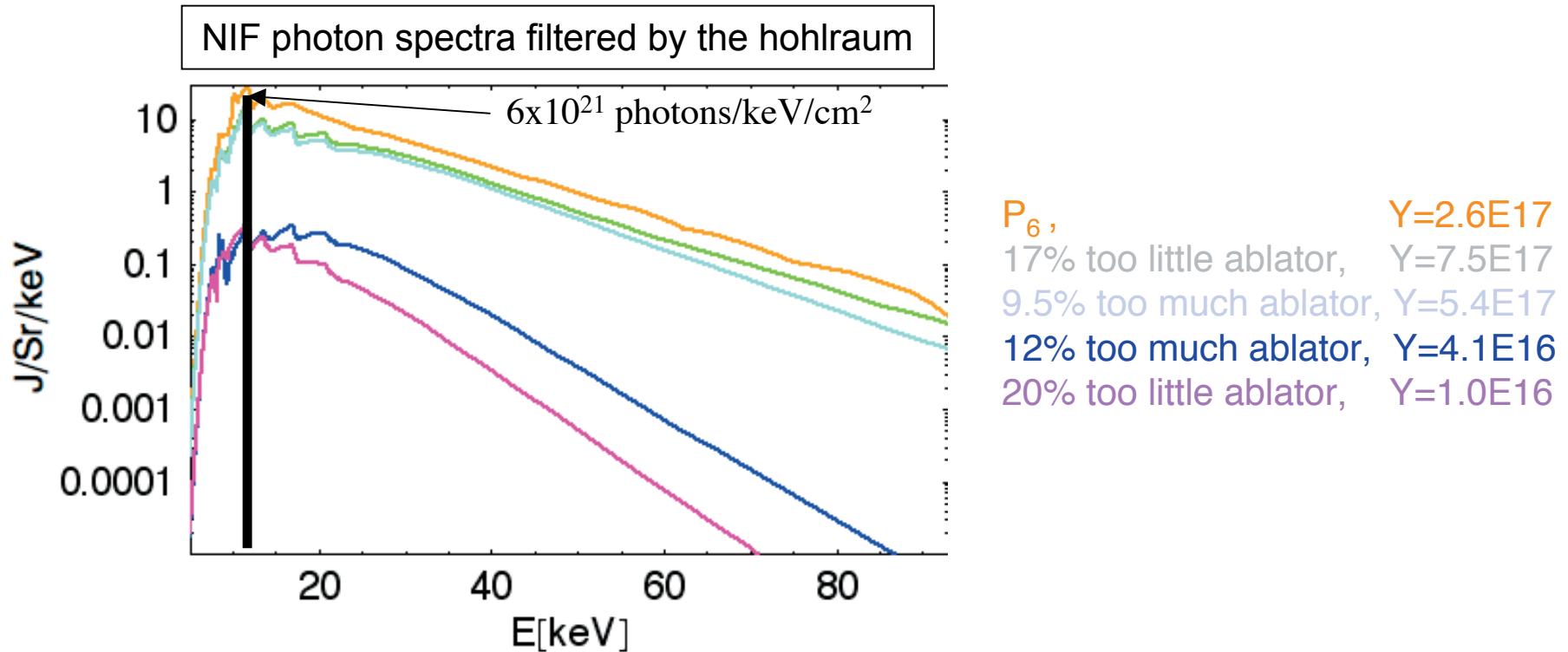


Most nuclear states are isomeric by NIF's standards

We've discussed the neutrons Now let's look at the photons



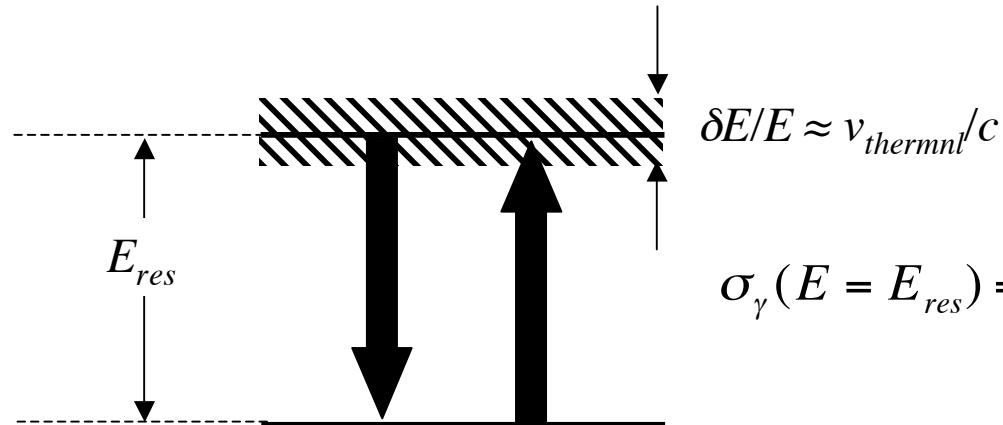
Even “failed” NIF shots produce huge photon fluxes



Spectrum is essentially Maxwell-Boltzmann with $k_B T \approx 10$ keV

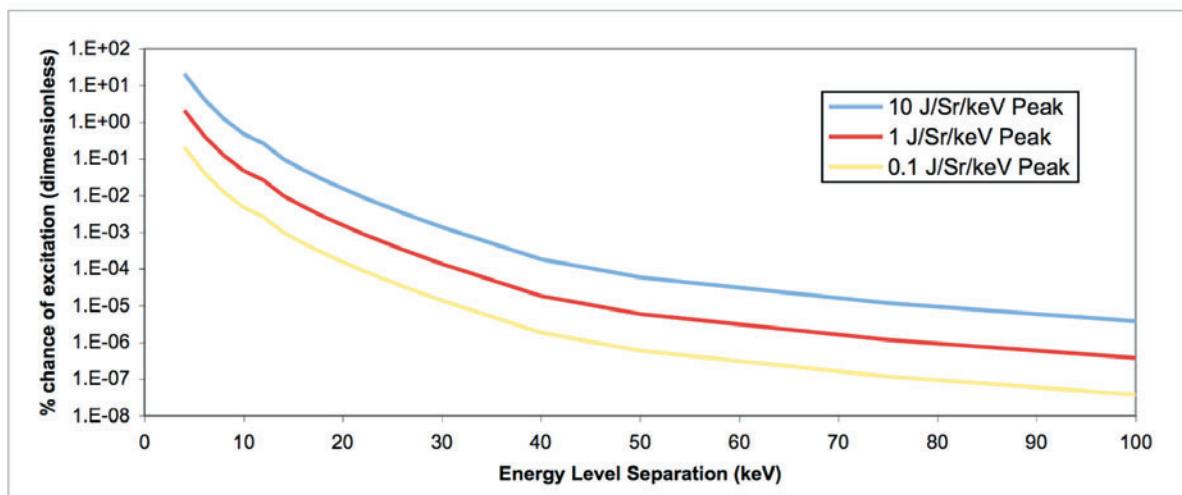
S.Hatchett simulations
Courtesy of R. Tommasini

This large photon flux opens the possibility of Nuclear Resonance Fluorescence (NRF)



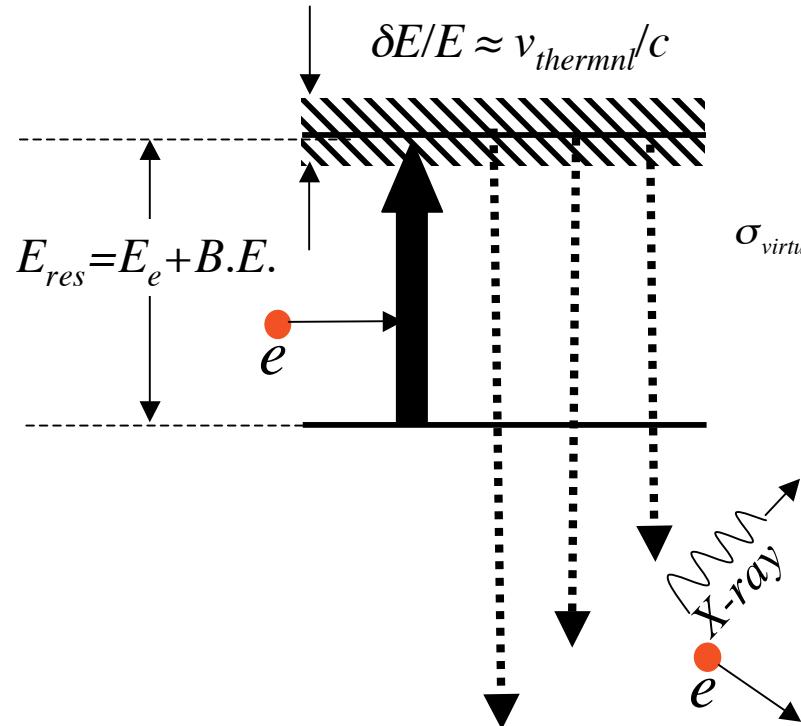
$$\sigma_\gamma(E = E_{res}) = 2.5 \times 10^3 b \left(\frac{1 \text{ MeV}}{E_{res}} \right)^2 \left(\frac{2J_j + 1}{2J_i + 1} \right)$$

$$\sigma_{NRF} = \sigma_\gamma \frac{\Gamma_0}{\Gamma_{thermal}}$$



Low energy excited states will be populated at significant levels

There is also a large electron flux which could induce Time Reversed Internal Conversion (TRIC)



$$\sigma_{virtual-\gamma}(E_e = E_{res} - B.E._e) = 2.5 \times 10^3 b \left(\frac{1 \text{ MeV}}{E_{res} - B.E._e} \right)^2 \left(\frac{2J_j + 1}{2J_i + 1} \right)$$

$$\sigma_{TRIC} = \sigma_{IC} \frac{(1 + \alpha)\Gamma_0}{\Gamma_{thermal}}$$

This effect is boosted relative to NRF by a factor of α

Excited state J and π have a strong effect on thermal (n,γ) cross sections



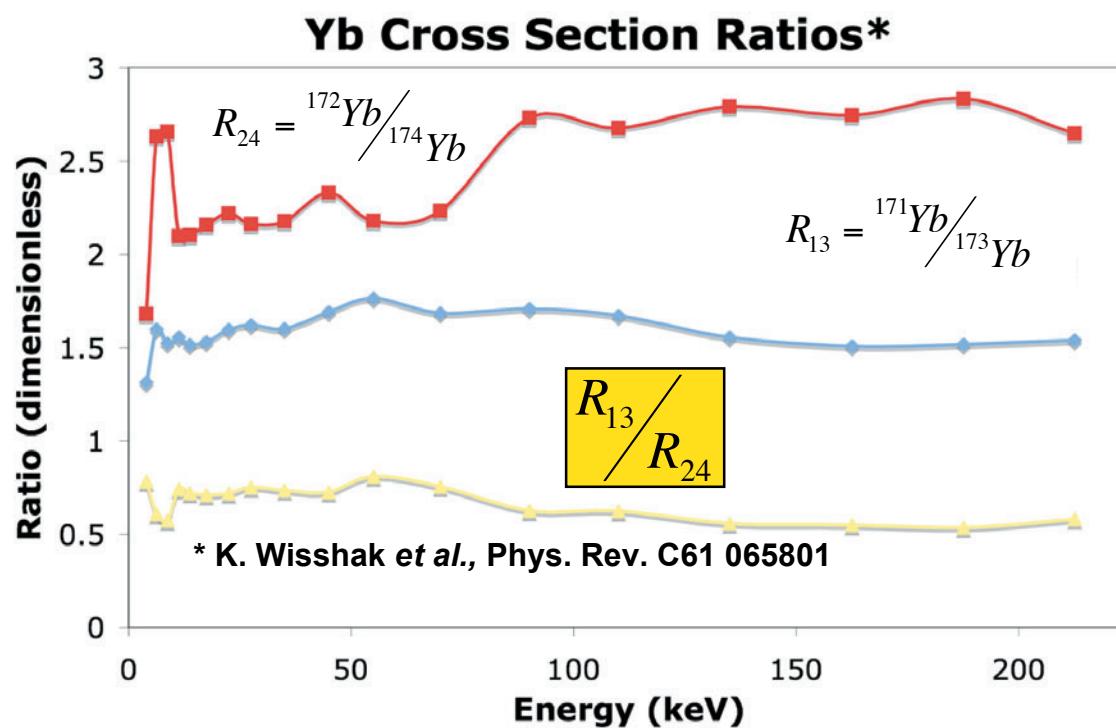
Nucleus	$J^\pi(g,m)$	$\sigma_{n,\gamma} (b)$
$^{177}\text{g,mLu}$	$7/2^+, 23/2^-$	1,000/3.2
$^{148}\text{g,mPm}$	$1^-, 6^-$	2,000/22,000
$^{60}\text{g,mCo}$	$5^+/2^+$	2.0/60
$^{58}\text{g,mCo}$	$2^+/5^+$	1,900/140,000

NIF allows exploration of these effects for many nuclei

(n, γ) is likely to be sensitive to J and π at stellar thermal energies ($k_B T \approx 10\text{-}30 \text{ keV}$)

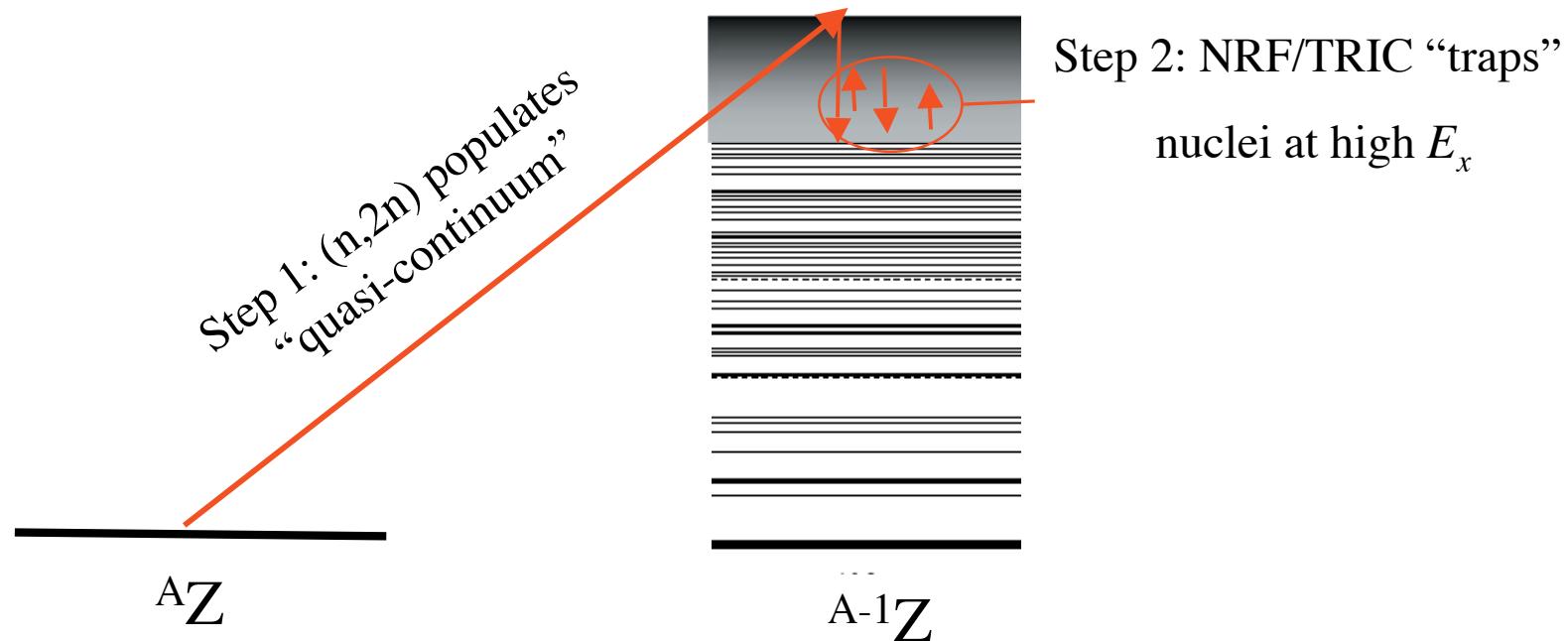


- No (n, γ) data exists for isomer & ground state of the same nucleus above reactor thermal temperatures
- Recent Karlsruhe measurement* of (n, γ) on Yb isotopes indicate potentially significant differences



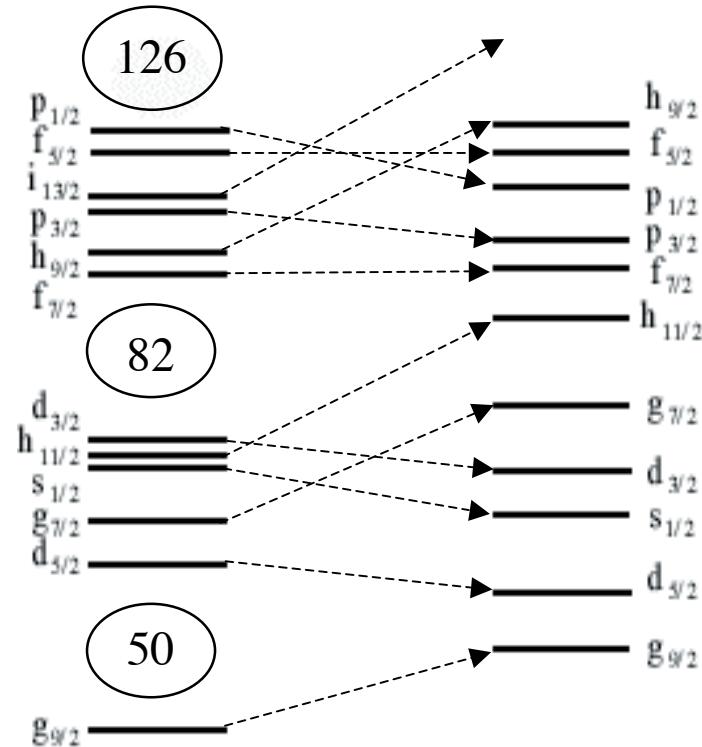
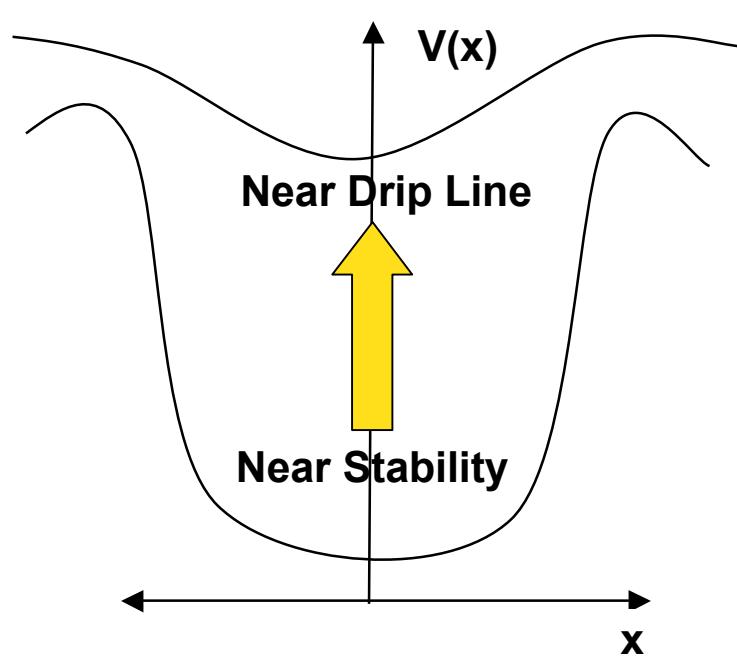
A	J $^\pi$	S _n (MeV)
171	1/2 ⁻	6.8
172	0 ⁺	8.0
173	5/2 ⁻	6.5
174	0 ⁺	7.5

Combining neutron and photon induced reactions provides the first direct probe of quasi-continuum physics



This is very sensitive to the lifetimes of quasi-continuum states
(photon strength functions)

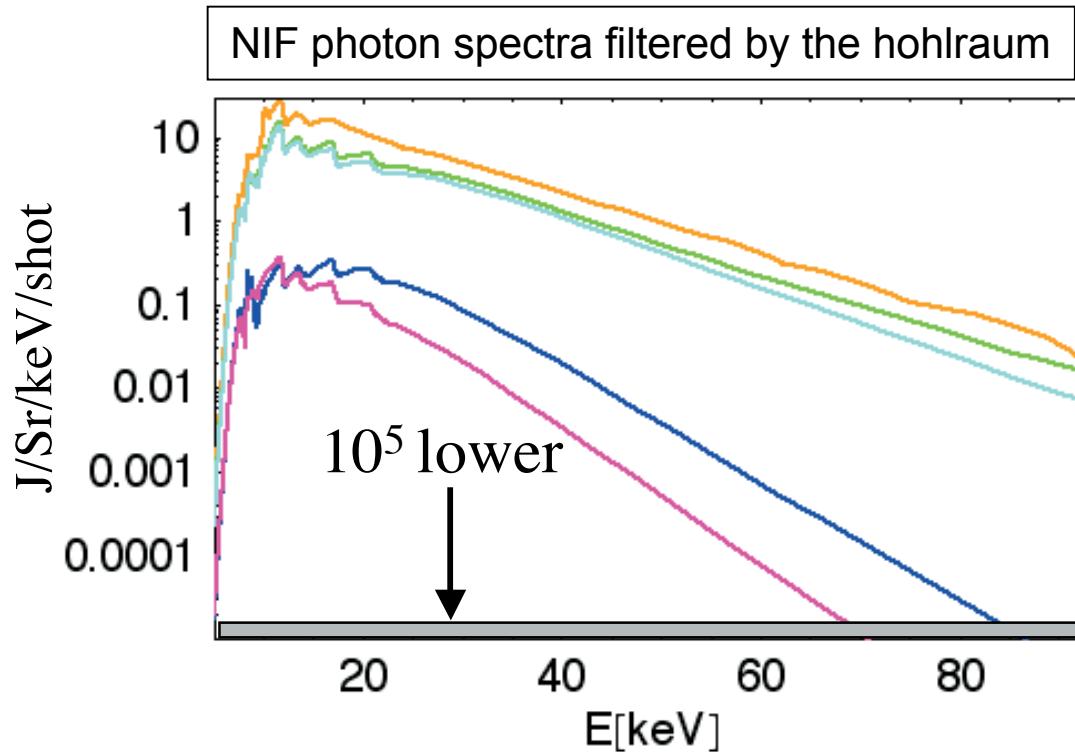
Reactions on excited states could provide insight into the variation of nuclear structure with temperature



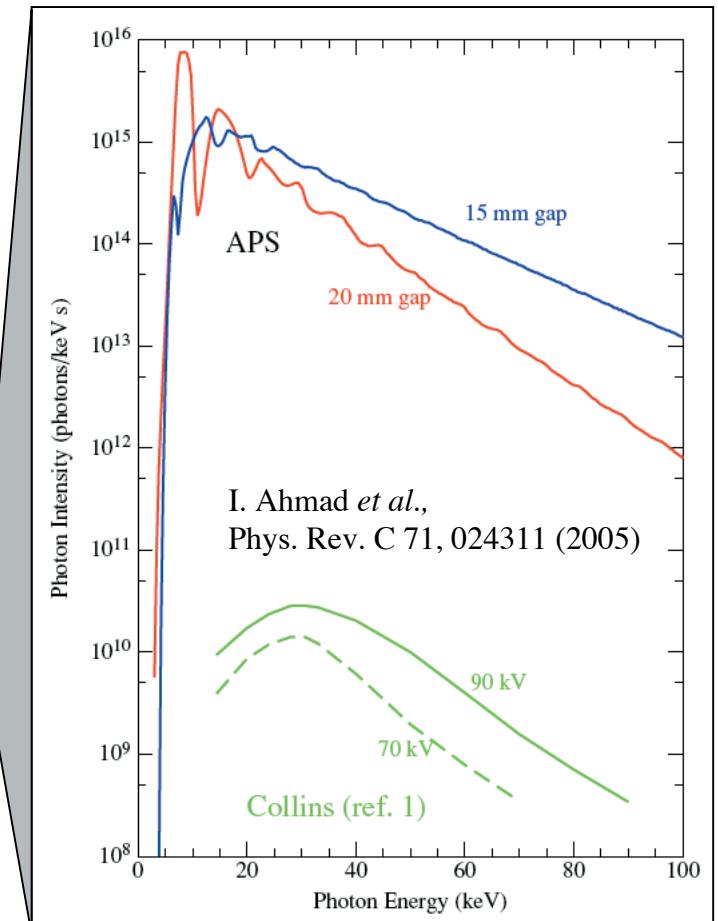
This could cause significant changes in $\rho(E, J^\pi)$

Which in turn effects reaction rates

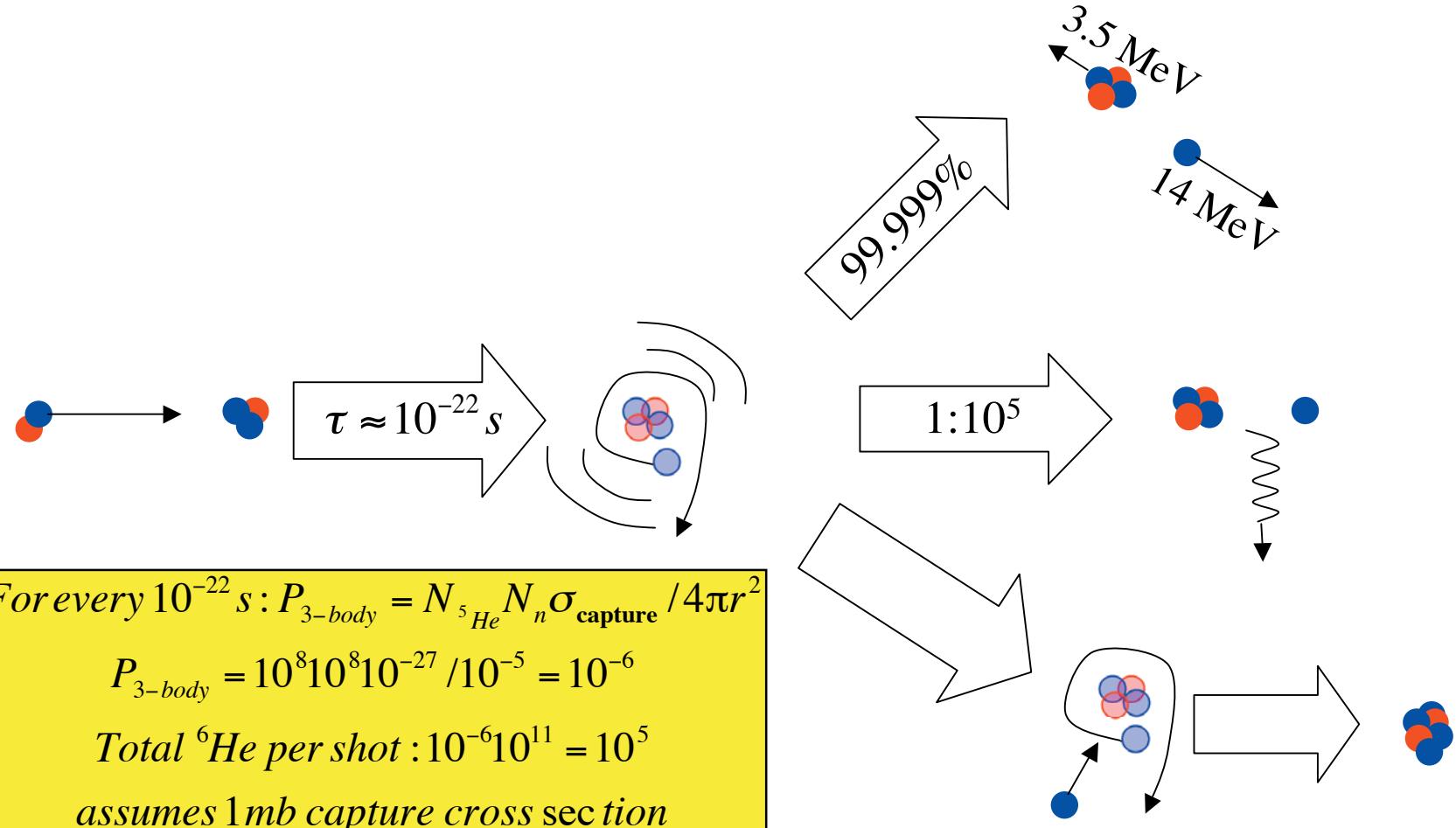
How does NIF compare with other photon sources used to stimulate isomer decay?



Stimulated isomer
emission becomes a real
possibility using NIF



NIF may allow the first direct observation of the shortest lived nuclear state: A 3-body reaction



$\alpha + \alpha + n \rightarrow ^9\text{Be}$ also possible

Conclusions



- The large neutron and photon flux at NIF offers the first possibility of studying reactions on non-isomeric nuclear states for the first time.
 - Quasi-continuum states at $E_x \approx S_n$
 - (n,x) reactions on low-lying excited states to study spin effects
 - Applicable to s-process nucleosynthesis
 - Exploring the effects of J and π on reaction cross sections
- NIF offers the brightest photon sources for NRF and TRIC to search for stimulated decay from isomers.
- NIF will be using radiochemistry as a diagnostic
 - Collection capabilities will be developed by LLNL+partners
 - Science efforts get to “tag along”
- External scientific collaboration is being encouraged
 - NIF will have a “PAC” that decides on “shot” time

What we want are your ideas



- Tools (both experimental and computational) are available.
- Scientific collaborations are welcome
 - Nuclear Astrophysics measurements
 - Nuclear Structure/Reactions measurements
 - Nuclear Chemistry
 - Gas and Plasma phase radiochemistry is particularly important for collection of non-gaseous products.
- LLNL is advertising for a Roger Batzel Nuclear Chemistry Post-doctoral position

NIFfler Collaborators



R.D. Hoffman, M.A. Stoyer, D.L. Bleuel*, D.H.G. Schneider,
K. Moody, C. Cerjan, D. Shaughnessy, S. Libby, R. Boyd
LLNL

L.G. Moretto, L.W. Phair, I.Y. Lee, M.A. McMahan
LBNL

U. Greife, A. McEvoy*, N. Sunde*
Colorado School of Mines

S. Siem, M. Guttormsen, A.C. Larsen*
University of Oslo

S. Grimes, A. Schiller
Ohio University